APPENDIX B: PV Module Operating Characteristics Drive *NEC* Requirements

INTRODUCTION

As the photovoltaic (PV) power industry moves into a mainstream position in the generation of electrical power, some people question the seemingly conservative requirements established by Underwriters Laboratories (UL) and the *National Electrical Code* (*NEC*) for system and installation safety. This short discourse will address those concerns and highlight the unique characteristics of PV systems that dictate the requirements.

The *National Electrical Code* (*NEC*) is written with the requirement that all equipment and installations are approved for safety by the authority having jurisdiction (AHJ) to enforce the *NEC* requirements in a particular location. The AHJ readily admits to not having the resources to verify the safety of the required equipment and relies exclusively on the testing and listing of the equipment by independent testing laboratories such as Underwriters Laboratories (UL). The AHJ also relies on the installation requirements for field wiring specified in the *NEC* to ensure safe installations and use of the listed equipment.

The standards published by UL and the material in the *NEC* are closely harmonized by engineers and technicians throughout the electrical equipment industry, the electrical construction trades, the national laboratories, the scientific community, and the electrical inspector associations. The UL Standards are technical in nature with very specific requirements on the construction and testing of equipment for safety. They in turn are coordinated with the construction standards published by the National Electrical Manufacturers Association (NEMA). The *NEC*, however, is deliberately written in a manner to allow uniform application by electricians, electrical contractors, and electrical inspectors in the field.

The use of listed equipment (by UL or other nationally recognized testing laboratory) ensures that the equipment meets well-established safety standards. The application of the requirements in the *NEC* ensures that the listed equipment is properly connected with field wiring and is installed in a manner that will result in an essentially hazard-free system. The use of listed equipment and installing that equipment according to the requirements in the *NEC* will contribute greatly not only to safety, but also the durability, performance, and longevity of the system.

UNSPECIFIED DETAILS

The *NEC* does not present many highly detailed technical specifications. For example, the term "rated output" is used in several cases with respect to PV equipment. The conditions under which the rating is determined are not specified. The definitions of the rating conditions (such as Standard Test Conditions (STC) for PV modules) are made in the UL Standards that establish the rated output. This procedure is appropriate because of the *NEC* level of writing and the lack of appropriate test equipment available to the *NEC* user or inspector.

NEC REQUIREMENTS BASED ON MODULE PERFORMANCE

Voltage

Section 690.7 of the *NEC* establishes a temperature-dependent voltage correction factor that is to be applied to the rated (at STC) open-circuit voltage (Voc) in order to establish the system voltage. This factor on the open-circuit voltage is needed because, as the operating temperature of the module decreases, Voc increases. The rated Voc is measured at a temperature of 25°C and while the normal operating temperature is 40-50°C when ambient temperatures are around 20°C, there is nothing to prevent sub-zero ambient temperatures from yielding operating temperatures significantly below the 25°C standard test condition.

A typical crystalline silicon module will have a voltage coefficient of -0.38%/°C. A system with a rated open-circuit voltage of 595 volts at 25°C might be exposed to ambient temperatures of -30°C. This voltage (595V) could be handled by the common 600-volt rated conductors and switchgear. At dawn and dusk conditions, the module will be at the ambient temperature of -30°C, will not experience any significant solar heating, and can generate open-circuit voltages of 719 volts (595 x (1 - (25 -(-30) x -0.0038)). This voltage substantially exceeds the capability of 600-volt rated conductors, fuses, switchgear, and other equipment. High wind speeds can also cause modules to operate at or near ambient temperatures, even in the presence of moderate levels of sunlight. The very real possibility of this type of condition substantiates the *NEC* requirement for the temperature dependent factor on the rated open-circuit voltage.

Thin-film PV technologies may have other voltage-temperature relationships, and the manufacturers of modules employing such technologies should be consulted for the appropriate data.

Current

NEC Section 690.8(A) requires that the rated (at STC) short-circuit current of the PV module be multiplied by 125% before any other factors, such as continuous current and conduit fill factors, are applied. This factor is to provide a safe margin for wire sizes and overcurrent devices when the irradiance exceeds the standard 1000 W/m2. Depending on season, local weather conditions, and atmospheric dust and humidity, irradiance exceeds 1000 W/m2 every day around solar noon. The time can be as long as four hours with irradiance values that approach 1200 W/m2, again depending on the aforementioned conditions and the type of tracking system being used. These daily irradiance values can increase short-circuit currents 20% over the 1000 W/m2 value. Since these increased currents can be present for three hours or more, they are considered continuous currents. By multiplying the short-circuit current by 125%, the PV output currents are adjusted in a manner that puts them on the same basis as other continuous currents in the *NEC*

Enhanced irradiance due to reflective surfaces such as sand, snow, or white roofs, and even nearby bodies of water can increase short-circuit currents by substantial amounts and for significant periods of time. Reflections from cumulus clouds also can increase irradiance by as much as 50%. These transient factors are not considered continuous and are not addressed by either UL or the *NEC*

Another factor that needs to be addressed is that PV modules typically operate at 30-40°C above the ambient temperatures when not exposed to cooling breezes. In crystalline silicon PV modules, the short-circuit current increases as the temperature increases. A typical factor might be 0.1%/°C. If the module operating temperature was 60°C (35°C over the STC of 25°C), the short-circuit current would be 3.5% greater than the rated value. PV modules have been measured operating over 75°C. The combination of increased operating temperatures, irradiances over 1000 W/m2 around solar noon, and the possibility of enhanced irradiance provide additional justification for the *NEC* requirement [690.8(A)] of 125% on the rated short-circuit current.

ADDITIONAL *NEC* REQUIREMENTS

The *NEC* requires that the continuous current of any circuit be multiplied by 125% before calculating the ampacity of any cable or the rating of any overcurrent device used in these circuits [690.8(B) and 240]. This factor is in addition to the required 125% discussed above and is needed to ensure that overcurrent devices and conductors are not operated above 80% of rating.

Since short-circuit currents in excess of the rated value are possible from the discussion of the Section 690.8(A) requirements above, and these currents are independent of the requirements established by Section 690.8(B), the *NEC* dictates that both factors will be used at the same time. This yields a multiplier on short-circuit current of 1.56 (125% x 125%).

The *NEC* also requires that the ampacity of conductors be derated for the operating temperature of the conductor. This is a requirement because the ampacity of cables is given for cables operating in an ambient temperature of 30°C. In PV systems, cables are operated in an outdoor environment and should be subjected at least to a temperature derating due to an ambient temperature of 40°C to 45°C. PV modules operate at high temperatures and, in some installations, may be over 75°C. Concentrating modules operate at even higher temperatures. The temperatures in module junction boxes approach these temperatures. Conductors in free air that lie against the back of these modules are also exposed to these temperatures. These high temperatures require that the ampacity of cables be derated by factors of 0.33 to 0.58 depending on cable type, installation method (free air or conduit), and the temperature rating of the insulation [310.16, 310.17].

Cables in conduit where the conduit is exposed to the direct rays of the sun are also exposed to elevated operating temperatures.

Cables with insulation rated at 60°C have no ampacity at all when operated in environments with ambient temperatures over 55°C. This precludes their use in most PV systems. Cables with 75°C insulation have no ampacity when operated in ambient temperatures above 70°C. Because PV modules may operate at temperatures in the 45-75°C range, it is strongly suggested that only cables with an insulation rated at 90°C be used.

SUMMARY

The conditions under which PV modules operate (high and low ambient temperatures, high and low winds, high and low levels of sunlight) and the electrical characteristics of those modules dictate that all of the requirements in the *NEC* be fully considered and applied.

There appears to be little question that the temperature-dependent correction factor on voltage is necessary in any location where the ambient temperature drops below 25°C. Even though the PV system can provide little current under open-circuit voltage conditions, these high voltages can damage electronic equipment and stress conductors and other equipment by exceeding their voltage breakdown ratings.

In ambient temperatures from 25 to 40°C and above, module short-circuit currents are increased at the same time conductors are being subjected to higher operating temperatures. Irradiance values over the standard rating condition may occur every day. Therefore the *NEC* requirements for adjusting the short-circuit current are necessary to ensure a safe and long-lived system.